Deriving Historical Total Solar Irradiance from Lunar Borehole Temperatures

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[1] We study the feasibility of deriving historical TSI (Total Solar Irradiance) from lunar borehole temperatures. As the Moon lacks Earth's dynamic features, lunar borehole temperatures are primarily driven by solar forcing. Using Apollo observed lunar regolith properties, we computed present-day lunar regolith temperature profiles for lunar tropical, mid-latitude, and polar regions for two scenarios of solar forcing reconstructed by Lean [2000] and Wang, Lean, and Sheeley [2005]. Results show that these scenarios can be distinguished by easily detectable differences in temperature, on the order of 0.01 K and larger depending on latitude, within ~10 m depth of the Moon's surface. Our results provide a physical basis and guidelines for reconstructing historical TSI from data obtainable in future lunar exploration. This work qualitatively confirms and updates earlier results of Huang [2004], and clarifies their dependence on variations in the background TSI and on the choice of lunar latitude.

1. Introduction

[2] A key prerequisite for understanding human impacts on Earth's changing climate is a reliable estimate of the impacts of solar variations, which in turn requires a definitive reconstruction of long-term variations in the Sun's total solar irradiance (TSI). Variations of TSI in recent decades directly measured by radiometers flown onboard several satellites have provided reliable short-term variations for timescales up to the Sun's 11-year solar activity cycle, but the instrumental record has not yet led to a consensus result for solar variations on multi-decadal and longer timescales. Variations of solar activity during recent centuries have been reconstructed from data on sunspots [*Lean*, 2000; *Wang, Lean and Sheeley*, 2005] and other indirect proxies such as ^{10}Be in ice cores [*Usoskin et al.*, 2004]. However, these proxy reconstructions have not yet led to any consensus on long-term irradiance changes. Thus the magnitude of the external forcing of climate by a change of the Sun's energy input to the Earth system between now and pre-industrial times is considered highly uncertain, as compared to the more well-understood climate forcing due to changes in greenhouse gases.

[3] New plans to explore the Moon provide a unique opportunity to resolve this climate conundrum, by completing the lunar heat flow experiment first attempted by Apollo 15, and applying it to understand the Sun's variations and consequent influence on Earth's climate, and thus to better understand the relative importance of the human influences on climate such as global greenhouse warming. Measurement of the temperature profile in a lunar borehole enables the reconstruction of TSI back through the Maunder Minimum of solar activity and the so-called Little Ice Age. The lunar regolith, free of atmosphere, biosphere, hydrosphere and human activities, is directly heated by the variable Sun, so the temperature variations at the lunar surface and the subsequent heating of the lunar regolith are dominated by variations in the solar input. The observations from HFEs in Apollo 15 and 17 in 1971 and 1972 show very low thermal diffusivity of the lunar regolith (~10^{-8} m^2/s). Thus downward propagation of solar forcing induced surface temperature variations is confined to the top layer of lunar regolith.

[4] Long-term terrestrial surface temperature variations are forced by non-solar and solar surface variations. As on the Moon, they propagate downward and are recorded in terrestrial borehole temperature profiles. The terrestrial borehole project was successfully conducted with several boreholes of ~500 m depth mainly around North America [*Huang et al.*, 2000] to derive temperature change for the last 500 years. Reconstructed surface temperature variations from these boreholes have shown gradual warming since the 16th century "Little Ice Age", with more rapid warming during the second half of the 20th century. Such warming agrees with results from the instrumental record, and also from dendroclimatology based on tree-ring width patterns [*Mann et al.*, 1999]. The reconstructed surface temperature from the terrestrial borehole temperature profiles captures the multi-centennial trend as well as the multi-decadal warming, though it is relatively insensitive to intra-decadal variations. Huang [2004] further suggested that "lunar surface temperature carries important information on both solar and terrestrial radiation" and also called for "borehole observatories on the Moon."

[5] This paper reports the feasibility of reconstructing TSI from the lunar regolith using a heat flow model with observed thermal properties from Apollo HFEs for two TSI scenarios [*Lean*, 2000; *Wang, Lean and Sheeley*, 2005]. We first describe the exploration plan for HFE on the moon in section 2, and briefly review the HFEs during the Apollo mission in Section 3. The heat flow model is described in section 4 followed by the results in section 5. The results are summarized and discussed in the final section.

2. Exploration Plans

[6] The Apollo program's scientific results help in understanding the physical processes of the Moon, and also provide clues to reconstruct the historical TSI. With experience from the Apollo missions, future lunar exploration is expected to provide in-depth comprehension

of the evolution of the solar system, and of historical TSI.

[7] Let us summarize the requirements for a successful experiment. First, we need to know the optimal depth of lunar regolith to retrieve historical TSI and the typical strength of signal from temperature anomalies induced by the solar forcing. Results from this study demonstrate that the signatures of multi-centennial TSI variations are preserved in the upper layer of lunar regolith about 10 m thick. The temperature anomaly arising from variations in TSI over the past ~500 years is about 0.01~0.015 K. A temperature measurement in a lunar borehole about 10m deep of sufficient precision to resolve a temperature anomaly of about 0.01K is required for this purpose.

[8] Second, drilling sites need to be carefully selected since the Moon is not uniformly covered with regolith. Lunar regolith, the top sector of accumulated sand on the base rock of the moon, grows as a result of micro-meteorite impacts, and extends to a depth of a few meters to over ten meters [*Muehlberger*, 1972]. High altitude plateaus of old geological sites hold thick layers of regolith. The regolith in more recently created craters is only a few meters thick. Deeper regolith naturally enables longer reconstruction of TSI, and thus highlands without any physical disturbance in historical times should be prime candidates for heat flux experimental sites. Temperature anomalies induced by TSI variations are largest near the equator, and detectable near the lunar poles. Measurements at either low or high latitudes are sufficient for reconstructing historical TSI. Further, a polar site may have the advantage of providing continuous solar power, while an equatorial experiment would need to survive the frigid lunar darkness.

[9] Third, since the temperature anomaly driven by long term solar forcing is small, any thermal or physical disturbance could ruin the recorded history of TSI in the regolith, and thus invalidate a purely solar interpretation of the observations. Thus the experiments should be conducted under well-managed conditions.

[10] The experiment of reconstructing historical TSI variations is a straightforward extension to the Apollo HFEs, with the emphasis now shifted from the temperature profile itself to the deviations of the profile due to historical solar irradiance variations. As with the HFEs, this experiment requires measurement of regolith thermal and radiative properties. Borehole samples are also of interest to other lunar exploration research, including the study of the structure and composition of the Moon, searching for lunar resources, and confirming the existence of ice in the lunar poles. A base on the Moon for several systematic measurements would enable more than just a few potential robotic experiments. Borehole temperature profiles from robotic missions could provide initial precise examinations of the heat flow of the Moon and the history of TSI variations. These could then be extended in time and to other sites with support from a permanent Moon base.

3. Review of Apollo 15 & 17 Heat Flow Experiments (HFEs)

[11] During the pioneering Apollo Moon missions, spacecraft landed on the Moon six times, and conducted several experiments including the HFEs. The HFEs were designed to estimate the rate of internal heat production by long-lived radioisotopes by measuring the properties of heat propagation in lunar subsurface layers. Temperatures were measured using two temperature-sensing probes with eight thermocouples embedded in the lunar subsurface spaced ~10 m apart. The thermocouples were attached to the probes so that the temperatures and the thermal diffusivity could be measured at different depths. Subsurface temperature variations were obtained with high accuracy (±0.05K) for more than 3.5 years by Apollo-15 & 17 [*Langseth et al*., 1972; *Langseth et al*, 1973].

[12] Fig. 2a shows an example of the surface temperature time series from the HFEs during the Apollo-15. The large diurnal variation of surface temperature from ~100K during the lunar nighttime to ~370K at the noon of lunar daytime is a result of the combination of low thermal diffusivity and the absence of atmosphere. Thermal diffusivity of lunar regolith is about $2\sim7\times10^{-9}$ m^2/s [*Keihm* 1984], about two orders of magnitude smaller than that of Earth's crust [*Seipold and Gutzeit*, 1982].

[13] The temperature variations as a response to solar forcing on the centennial time scale are limited to a top layer about 10 m thick from scale analysis. Assuming penetration depth of a periodic forcing depends only on thermal diffusivity, and noting diffusivity units are m^2/s, then to get a depth, we must multiply diffusivity by the time period in seconds, and take the square root. Using timescale of 300 years ~ $300\pi10^7$ s, since that approximate the time since the Maunder Minimum (see e.g. Fig. 3), we get: diffusion depth ~ $\left(10^{-8} m^2/s \times 300\pi 10^7 s\right)^{1/2}$ ~ 10 m. We confirm this later in Eq. (4).

4. Description of Model

[14] Temperature profiles of lunar regolith are governed by the standard heat conduction equation

$$\rho C_p \frac{\partial T(z,t)}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial T(z,t)}{\partial z}\right) \tag{1}$$

with boundary conditions

$$k \left.\frac{\partial T(z,t)}{\partial z}\right|_{z=0} = \varepsilon\sigma T(z,t)^4 - (1-\alpha)\cos(\theta_0) F(t) \tag{2}$$

$$k \left.\frac{\partial T(z,t)}{\partial z}\right|_{z=z_b} = H \tag{3}$$

where the variables are defined as follows: T, temperature; ρ, the density of regolith; C_p, the specific heat; k, the thermal conductivity; ε, the emissivity of lunar regolith; σ, the Stefan-Boltzmann constant; α, the surface albedo; H, the internal heat flux at the bottom of regolith z_b; z, the depth from the surface of the regolith layer; t, the time; $F(t)$, the TSI at Moon-Sun distance at time t; θ_0, the solar zenith angle. The net radiative flux as the sum of emitted thermal radiation and the absorption of solar radiation, the first and the second term on the right hand side of Eq. (2) respectively, determines the heat flow at the upper boundary. Eq. (3) describes a net heat flow from below at the lower boundary of the computational domain.

[15] The net radiative flux at the surface is the primary driving force for the lunar climate. Before proceeding to a detailed analysis we present energy budgets in Fig. 1 to show schematically the role of each individual component to the Moon's climate. During daytime, the Sun provides an average input about 662 W/m^2 at the lunar surface at mid-latitudes, with 120 W/m^2 reflected back to space, leaving 542 W/m^2 to be absorbed by the regolith layer. The absorbed solar radiation is not balanced by the emitted thermal radiation of about 536 W/m^2. The average net energy flux is about 6 W/m^2, and is transported downward and stored as heat in the top layer of the regolith about 0.5 m thick. During the Moon's nighttime, the heat stored during the daytime is finally transported to the surface and emitted to space. Radiation from the Earth is about 1~2

orders of magnitude smaller than the heat storage, but it is ~1 order of magnitude larger than the internal heat flux (H=0.018W/m^2). The historical variation of the terrestrial radiation is ignored. The energy budgets for the equator and lunar pole are presented in parentheses in the same figure. The energy budgets may not be precise; however, the sketch in Fig. 1 quantifies the relative importance of each individual component of energy budgets in determining the climate of the Moon.

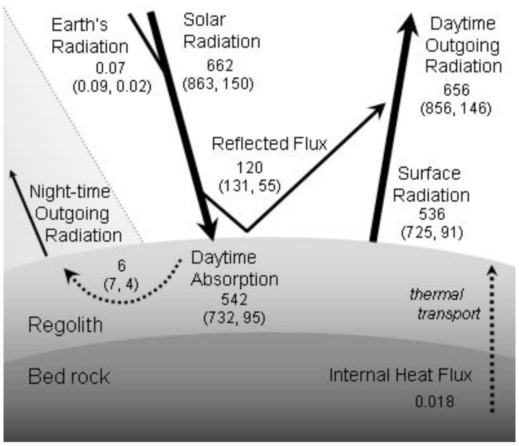

Figure 1. Energy balance of lunar system with unit of W/m^2 for mid-latitude. Energy budgets for the equator and the polar sites are presented in parentheses respectively.

[16] To fully understand the relationship between the historical TSI variations and consequent impacts on the present-day lunar borehole temperatures, we need to solve the governing Eq. (1). In computing the present-day lunar borehole temperatures, regolith properties and a constant heat flow (H=0.018W/m^2) derived from Apollo HFEs are used [*Keihm*, 1984]. The input historical variation of TSI is not well known. This can be seen in two scenarios of reconstructed TSI (Fig. 3). The two scenarios agree well in the recent solar 11-year cycles, but differ about 2W/m^2 during Maunder Minimum about 330 years ago. Using the two scenarios as inputs in the numerical computations, we examine if the related temperature responses are distinguishable. Since the TSI in all scenarios is given at 1AU, we use the JPL Planetary and Lunar Ephemerides [*Standish*, 1998] to compute Moon-Sun distance to determine $F(t)$ as well as the solar zenith angle in Eq. (2).

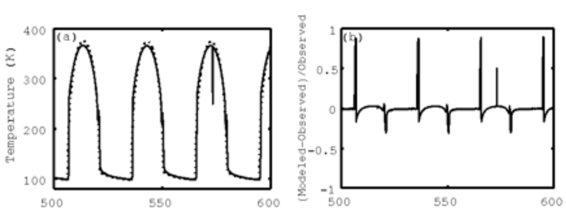

Figure 2. (a) Lunar surface temperatures obtained by HFE of Apollo15 (solid line) and the modeled surface temperatures obtained for the same site (dotted line); (b) relative difference between modeled and observed surface temperatures.

[17] We check model performance by comparing modeled temperatures to observations at Apollo-15 site. Numerical results adequately reproduces the observed surface temperatures except near sunrise and sunset (Fig. 2a and 2b). Large difference between modeled and observed surface temperature near sunrise and sunset is likely due to local surface topographic variations [*e.g.*, *Langseth et al*, 1972] not accounted for in our 1D model. During the Apollo HFEs total solar eclipse occurred several times at the Apollo 15 site resulting in an abrupt decrease in the surface temperature at solar noon. As our interest is in climatic changes, this short time disturbance is ignored in the modeling study.

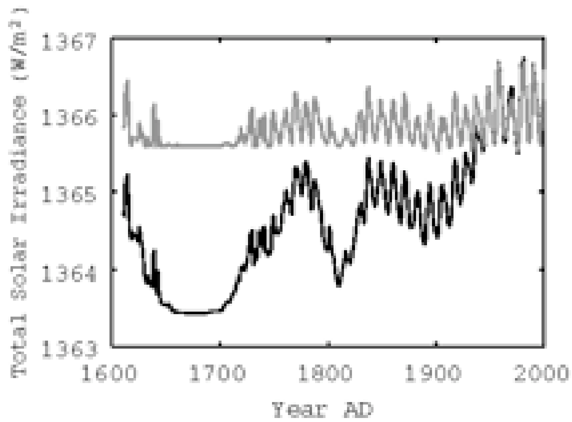

Figure 3. TSI scenarios by Lean [2000] (black line) and Wang, Lean and Sheeley [2005] (gray line) introduced to the heat flow computations.

5. Model Results

[18] As a first step in understanding the behavior of heat penetration in the lunar regolith, we examined the e-folding depth for ideal periodic temperature variations at the surface. For a homogeneous medium of diffusivity, K, with a sinusoidal surface temperature variation, the e-folding penetration depth is given by:

$$z_e = \sqrt{\frac{K P}{\pi}} \tag{4}$$

where P is period of the variation .

[19] The monthly and annual periodic variations of temperatures at the surface are strongly attenuated within the top 0.3 m of the regolith. Variations in TSI related to 11-year solar activity are primarily confined to the first couple of meters of regolith layer. For a timescale of about 400 years (or P~800 years) for the Maunder Minimum, the penetration depth is about 8 meters. Therefore, a typical 10-meter deep borehole is required in reconstructing TSI during Maunder Minimum. Also, exponential attenuation of the periodic variations indicates that we will need high-precision measurements in reconstructing TSI from lunar regolith.

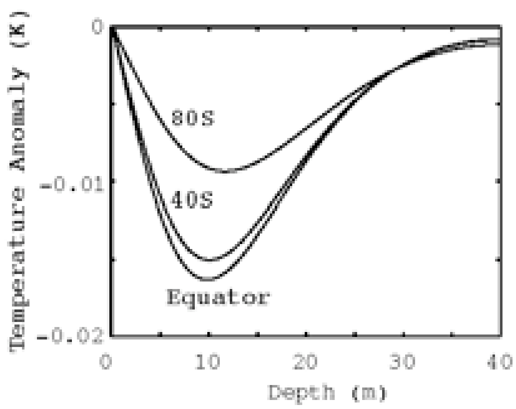

Figure 4. Temperature anomalies as response to two

scenarios of reconstructed TSI in Fig. 3 at the equator, mid-latitude (40°S) and near the south pole (80°S).

[20] The penetration depth provides a rough estimate of regolith depth required to resolve TSI variations on timescales of interest. In reality the thermal diffusivity depends on temperature [*Keihm*, 1984]. The surface temperature is not a simple sinusoidal, and historical solar forcing plays an important role in the lunar regolith temperature profile. A detailed analysis is needed to estimate the vertical structure of temperature anomalies as a result of long-term solar forcing. Two present-day temperature profiles $T_1(z)$ and $T_2(z)$ in year 2000 AD are computed using the two TSI scenarios of Lean [2000] and of Wang, Lean and Sheeley [2005] for 1610-2000 AD, respectively. Using the difference of the two temperature profiles, we examine the possible temperature anomalies (*i.e.*, $\Delta T(z)= T_1(z)-T_2(z)$) caused by different solar forcing of the two scenarios.

[21] Fig. 4 shows the temperature anomalies expected for the equatorial, mid-latitude and the polar site. Since the timescales for both TSI models are about the same as reductions in TSI during the Maunder Minimum, a larger reduction of TSI in the case of Lean [2000] leads to a negative anomaly compared to the scenario of Wang, Lean and Sheeley [2005]. The magnitude of temperature anomaly increases as a function of depth, reaching a maximum of 0.016 K, 0.015 K, and 0.009 K for the equatorial, mid-latitude, and polar sites, respectively, at a depth of about 10 m, and decreases gradually as it gets deeper. The magnitude of the peak of the anomaly depends on the latitude. However the depth where the peak occurs is independent of latitude. This is consistent with the penetration depth defined in Eq. (4).

6. Summary and Discussion

[22] We have examined the feasibility of using lunar temperature profiles to reconstruct TSI back to the Maunder Minimum time period. A simple analysis shows that the penetration depth in the lunar regolith is about 10 m for a periodic surface temperature variation with a timescale of 400 years. A detailed analysis is performed to quantify the lunar borehole temperature response to two reconstructed TSI time series. We found that (1) the signals of variations of TSI in centennial timescales are recorded as temperature anomalies confined in an optimal depth about 10 meter thick in lunar regolith; (2) the magnitude of optimal temperature anomaly ranges from ~0.01 K near the lunar poles to ~0.017 K at the equator. The optimal depth of 10 meters is consistent with the simple penetration depth.

[23] The results of this study are based on two reconstructed TSI time series. With similar TSI in the few recent solar cycles, the two time series diverge about 70 years from the present, with the largest difference about 2 W/m^2 during Maunder Minimum around 330 years ago. The two scenarios represent the current understanding of variations of TSI on the centennial timescale. To distinguish the two TSI scenarios one requires a temperature measurement precision that can resolve an optimal temperature difference of 0.01 K in a lunar borehole about 10 m thick.

[24] In order to achieve accurate reconstruction of TSI from lunar borehole temperatures, a location near the equator is most desirable, although the signal of TSI variations in lunar borehole temperatures is detectable near the lunar poles. Since the heat flow depends on the thermal conductivity, density and specific heat, which presumably vary with depth, the experiment requires measurements of these parameters with high spatial resolution in addition to the temperatures. Those parameters can be obtained from observations in future exploration, and will accordingly be implemented in our model.

[25] This research provides the fundamental physical basis and guidelines for reconstructing TSI back to the time period of the Maunder Minimum and Little Ice Age from lunar borehole temperatures from future lunar exploration. The results reported here are based on 1-D computations and Apollo HFE derived thermal properties. In reality, the terrain of lunar surface, bedrock with higher thermal conductivity at some depth and other possible heat sources, may affect borehole temperature profiles. In future research, we plan to extend the current 1D model to a 3D model to account for the observed topography of specific proposed experimental sites. We will further study the impact of the bedrock and other potential heat sources on borehole temperature profiles, and on reconstructions of historical values of TSI.

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References

Huang S, H. N. Pollack and P. Y. Shen (2000), *Nature*, *403*, 756-758.

Huang, S. (2004), Lunar regolith temperature as a monior of the radiation budget of Earth, paper presented at the SORCE Science Meeting, Meredith, New Hampshire, 27-29, October. (http://lasp.colorado.edu/sorce/news/2004ScienceMeeting/Meeting_Review.html)

Keihm, S. J. (1984), Icarus, *60*, 568–589.

Kopp, G., G. Lawrence and G. Rottman (2005), *Solar Physics*, *203*, 129-139.

Langseth, M. G., S. P. Clark, J. L. Chute, S. J. Keihm and A. E. Wechsler (1972), *Apollo 15 Prelim. Sci. Rep.*, NASA SP-289, 11-1 to 11-23.

Langseth, M. G., S. J. Keihm and J. L. Chute (1973), *Apollo 17 Prelim. Sci. Rep.*, NASA SP-330, 9-1 to 9-24.

Langseth, M. G., S. J. Keihm and K. Peters (1976), *Proc. 7th Lunar Sci. Conf.*, 3134-3171.

Lean, J., *Geophys. Res. Lett.*, (2000), *27*(16), 2425-2428.

Mann, M. E., R. S. Bradley and M. K. Hughes (1999), *Geophys. Res. Lett.*, *26*, 759-762.

Muehlberger, W. R. *et al.* (1972), *Apollo 16 Prelim. Sci. Rep.*, NASA SP-315,6-1 to 6-81.

Seipold, U. and W. Gutzeit (1982), Physics of the Earth and Planetary Interios, *29*, 69-72.

Standish, E.M. (1998), *JPL IOM*, 312, F-98-048.

Usoskin, I. G., K. Mursula, S. Solanki, M. Schüssler and K. Alanko (2004), Astronomy & Astrophysics, *413*, 745–751.

Wang, Y. M., J. L. Lean and N. R. Sheeley (2005), *Astrophys. J.*, *625*, 522-538.